AFRL-ML-WP-TR-1998-4191

CUT PROGRESSION DURING DYNAMOMETER TESTING OF FOREIGN OBJECT DAMAGED TYPE VII EXTRA HIGH PRESSURE AIRCRAFT TIRES SAE PAPER 912155

PETER C. VORUM

SEPTEMBER 1991

FINAL REPORT FOR 03/15/1984 – 06/15/1991

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THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	SEPTEMBER 1991	FINAL REPORT 03/15/1984 - 06/15/1991

4. TITLE AND SUBTITLE
CUT PROGRESSION DURING DYNAMOMETER TESTING OF FOREIGN OBJECT DAMAGED TYPE VII EXTRA HIGH PRESSURE AIRCRAFT TIRES; SAE PAPER 912155

5. FUNDING NUMBERS
C IN-HOUSE
PR 2402
TA 01
WU 47

6. AUTHOR(S)
PETER C. VORUM

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
MATERIALS AND MANUFACTURING DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AFB, OH 45433-7750

8. PERFORMING ORGANIZATION REPORT NUMBER
SOCIETY OF AUTOMOTIVE ENGINEERS TECHNICAL PAPER 912155

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
MATERIALS AND MANUFACTURING DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AFB, OH 45433-7750
POC: PETER C. VORUM, AFRL/MLBT, 937-255-9024

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-ML-WP-TR-1998-4191

11. SUPPLEMENTARY NOTES
THIS PAPER WAS PUBLISHED IN THE 1991 SAE TRANSACTIONS JOURNAL OF AEROSPACE

12a. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS
CUTTING, FOD, FOREIGN OBJECT DAMAGE, DYNAMOMETER, CUT PROGRESSION, DEBRIS, RUNWAY, TAXIWAY

15. NUMBER OF PAGES
18

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

912155

Cut Progression During Dynamometer Testing of Foreign Object Damaged Type VII Extra High Pressure Aircraft Tires

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ABSTRACT

Ground operations over rough surfaces and/or debris strewn taxiways and runways may result in cut damage to the tires. Cut progression during continued flight operations has not been seriously studied. This report will follow a group of Type VII Extra High Pressure tires which were damaged by running them over a debris strewn test bed, then run through alternating taxi-takeoff and landing-taxi tests on the 3.05 meter (120 inch) dynamometer in the Landing Gear Development Facility at Wright-Patterson Air Force Base. Only 1.3 - 23% of the debris struck by these tires resulted in cuts. While testing on the dynamometer, the cut depth grew rapidly until it reached the outer carcass ply, then slowed. The test group included new and recapped bias ply, and prototype radial main landing gear tires. This paper will summarize the tire tests and offer recommendations for future evaluation of the tires and materials.

TIRE cuts may result from operation over rough surfaces and/or over debris. This report follows cut progression during dynamometer testing of foreign object damaged Type VII Extra High Pressure aircraft tires (1)*. F-16 25.5 x 8.0 Main Landing Gear tires were run over a debris strewn field once, at the Naval Air Engineering Center (NAEC) at Lakehurst NJ. Selected tires considered here were run through alternated Taxi-Takeoff (TTO) segments and Landing-Taxi (LT) segments on the north carriage of the 3.05 m (120 inch) dynamometer in the Landing Gear Development Facility (LGDF) at Wright-Patterson Air Force Base Ohio. Three different tires were run:

first-time recapped bias tires,
new bias tires, and
prototype radial tires.

BACKGROUND

This effort is a part of a long-term research program between the Special Projects Group, Flight Dynamics Directorate, at Wright-Patterson Air Force Base Ohio; and the Engineering Services Center, at Tyndall Air Force Base Florida. The program examines the effect of debris on aircraft operations such as debris lofting, need for runway cleanliness requirements, and cut damage/progression to the tires (2). Previous tests of damaged tires (3) suggested that cut depth was a better indicator of tire condition than cut length. The analyses presented do not consider cut length.

The F-16 can operate from forward airfields. It is probable that the size and amount of debris scattered around runways, taxiways, and ramp areas would vary widely in a post attack environment.

Each tire ran over a debris strewn track one time, had cuts mapped, and was returned to Wright-Patterson for dynamometer testing. Upon return from NAEC, none of these tires was flight worthy. All would normally be removed immediately because of the damage that existed. During the laboratory testing it was shown that most of the new tires and some of the recapped tires might survive at least one takeoff and one landing in an emergency situation.

TEST FACILITY AND EQUIPMENT

TIRE CUTTING TEST VEHICLE - The Tire Cutting Test Vehicle (TCTV) at Lakehurst was used for a test of debris lofting, with an F-4 nose landing gear in place. That fixture was replaced with one that supported an F-16 main landing gear wheel assembly (see Figure 1). The following elements were varied on the test tire, the TCTV, and what the tire passed over:

Tire vertical load,
inflation pressure,

brake pressure (drag load), and

* Numbers in parentheses designate References at the end of the paper

FIGURE 1 - TIRE CUTTING TEST VEHICLE

turning angle (side load).

Vehicle speed.

Test bed length,
number of pieces of debris on the ground,
debris size and type (limestone vs metal fragments), and
debris ground pattern.

TEST INSTRUMENTATION - The Time-Load-Speed profiles of the TTO and LT segments were entered into the dynamometer computer, and run automatically. Internal air pressure was adjusted for flywheel curvature. The valve was closed at the beginning of the run so that air could not enter or leave the tire during the test segment. Contained air temperature and tread surface temperature were monitored.

The physical examination of the tire was done in a steel plate and wire mesh Safety Box (5), with tools such as a tire pressure which monitored the tire pressure of 689.5 kPa (100 psi), a standard cut depth gauge marked in 1/32 inch (0.8 mm) increments to measure the depth of the cuts, and a ruler marked in 1/16 inch (1.6 mm) increments to measure the length of the cuts.

APPROACH

Each tire was mapped for cuts after it came off of the TCTV. Dynamometer testing included map updates. In all cases, the tire surface was allowed to cool below 38° C (100° F) before anyone entered the dynamometer cell to remove the tire or to visually inspect the tread. It was not deflated until it had cooled, because early deflation might cause delamination of the carcass inner liner or other damage, unrelated to the scope of this program.

TEST SUMMARY

One hundred and twenty three tires were run at NAEC. Of these, 34 tires were selected for testing on the dynamometer. The number of dynamometer segments completed and causes for removal are presented in Table 1.

Table 1: Test Segments Completed and Cause for Removal

Tire type	Number of tires	Segments at failure	Reason for removal
Recap	2	1	stripped tread
	7	3	chunked/stripped/undercut portion of, or all of tread
	3	5	stripped tread
	1	7	chunked/undercut one rib
	13 tires		
New	1	3	chunked
	5	5	chunked/stripped
	1	6	undercutting
	5	** 6	** completed without failure
	1	7	stripped
	2	9	stripped/chunked/undercut
	1	11	chunked
	1	15	stripped
	17 tires		
Radial	1	3	stripped
	1	5	stripped
	2	** 6	** completed without failure
	4 tires		

The tires were broken into two Phases for dynamometer testing:

PHASE 1 - The tires were run to destruction on the dynamometer. Failure was due to one or more of the following parameters:

heat blow,
undercutting, and/or
tread chunking/stripping.

This group included all of the recapped tires and some of the new tires. Cut maps were updated after each dynamometer segment. The test process was very lengthy since each tire had to cool before removal from the dynamometer, was remapped in the Safety Box (5), and returned to the test queue. Remapping each tire after each segment resulted in a maximum daily test rate of six tires in 8 hours.

PHASE 2 - The tires were remapped only after the first TTO segment. They then remained on the dynamometer until destruction, or until three TTO segments and three LT segments were completed, whichever was first. This group included the balance of the new tires not tested in Phase 1, and all of the prototype radial tires.

Upon return from NAEC, 26 of the 30 bias ply tires had a number of cuts deeper than the Cut Limit; there was no Cut Limit indicated for the radial tires. There was little damage to the carcass of any dynamometer tested tire and no tire run on the dynamometer lost air pressure. Changes in surface flaws were erratic, such as:

new cuts or blemishes appeared,
blemishes opened into cuts,
cuts did not change,
cuts grew deeper or shallower,
cuts or blemishes disappeared,
cuts closed to become blemishes,
and some did a combination of all of the above

The Cut Limit locates the outer most carcass ply relative to the bottom of the groove. The Type VII Extra High Pressure tires may suffer damage to one ply layer and continue in use. As the recapped tires were run on the dynamometer, the mean depth of the cuts grew until it approached the Cut Limit depth. The mean depth of the cuts of the new tires grew slightly deeper than the Cut Limit.

At NAEC, more of the new tires were run over larger debris than the recapped tires, and sustained more initial cuts beyond limits than the recaps did. This difference in testing may have contributed to the progression of the new tire cuts, deeper into the carcass than what appeared on the recaps.

The reinforcing tread plies have an unknown effect on the cut. Other things may happen to the tread (chunking or undercutting), but the cut depth increase appears to stop or to slow greatly at the carcass limit. As is often seen in composites, the crack stops when it goes from an elastic material (rubber) into the reinforced material (rubber/carcass fiber).

TIME-LOAD-SPEED SPECIFICATIONS

On the dynamometer, each tire was run on a Time-Load-Speed (TLS) history described in Drawing 16VL002 (4):

Taxi-Takeoff segments were alternated with Landing-Taxi segments,
the "heavy" weight takeoff specification was used,
the normal landing weight specification was used,
a 2.3 km (7500 foot) taxi length was used to model a forward combat base, and
the tire was stopped momentarily between the taxi roll, and the takeoff or landing sequence (see Figures 2 and 3).

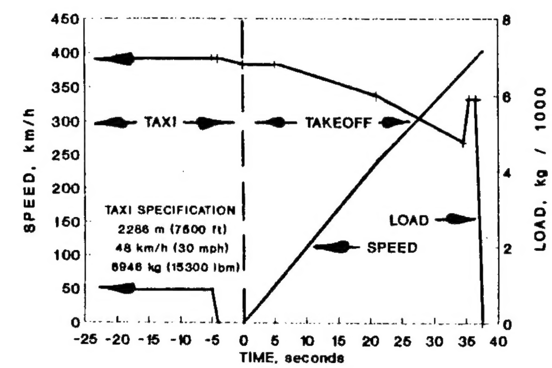


FIGURE 2: F-16 MAIN LANDING GEAR
TAXI-TAKEOFF: TIME vs SPEED and LOAD

In the takeoff segment, there is a "spike" load increase on the main landing gear tire as the nose of the aircraft rotates off of the ground at T = 34.5 seconds.

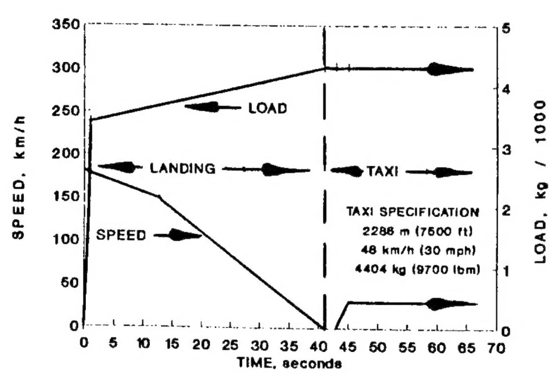


FIGURE 3: F-16 MAIN LANDING GEAR
LANDING-TAXI: TIME vs SPEED and LOAD

TIRE CONDITION RECORDS

DAMAGE CRITERIA - Damage limits for Type VII Extra High Pressure tires are published in MIL-T-5041, paragraph 3.4.10 (6). The criteria for immediate removal of a damaged tire is listed in Table 2.

DAMAGE RECORDS - The conventions presented in Figures 4 and 5 were used to document the position and orientation of the cuts. Each cut, puncture, blemish, or scuff was recorded under the procedure described in Reference 5. The elements listed in Table 3 were examined and recorded during the inspections. See the Appendix for damage descriptions.

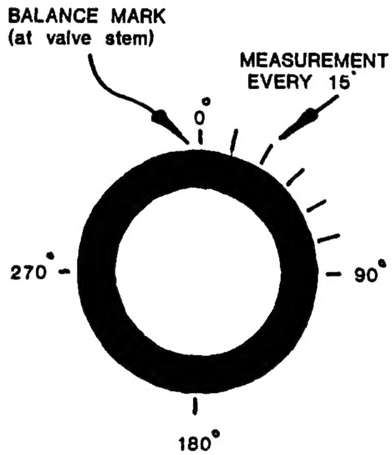


FIGURE 4: CUT MAP CONVENTIONS
SIDE VIEW

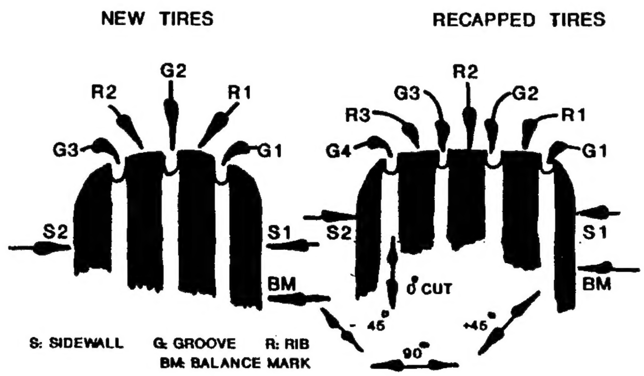


FIGURE 5: CUT MAP CONVENTIONS
TREAD VIEW

Table 2: Damage That is Cause for Removal

(1) Tread chunking that exceeds 6.5 cm sq (1.0 square inch area)
(2) Tread stripping (large scale chunking)
(3) Any amount of undercutting
(4) A heat blow that results in any chunking that exceeds limits, or if there is any undercutting
(5) Any cut deeper than the Cut Limit: no cut shall penetrate deeper than the first carcass ply layer. This limit was ignored for the term of this test

Table 3: Variables Recorded in Cut Maps

(1) Cut number
(2) Length in 1.6 mm (1/16 inch)
(3) Depth in 0.8 mm (1/32 inch)
(4) Circumferential position in degrees relative to the balance mark
(5) Lateral position across the face of the tread, i.e. groove, rib, or sidewall, with "SW 1" being the sidewall on the balance mark side of the tire
(6) Angle relative to the centerline groove, where:

Parallel to the groove is considered "0°"
Rotation less than 90° clockwise is "+ 45°"
Rotation less than 90° counter clockwise is "- 45 °"
Perpendicular to the center groove is "90°"

FAILURE MODES

In Phase 1 of these tests, the tires were run to destruction by chunking, stripping, and/or undercutting.

In Phase 2, the tires were run to destruction as in Phase 1, or until they completed three TTO and three LT segments, whichever came first.

Evidence of deterioration appeared on TTO and LT segments, but most damage-related failures were on a TTO segment. In the takeoff segment, the main tire load drops as the vehicle accelerates, but a short term, high load spike is imposed on the main tire at a time that corresponds to aircraft rotation. Most chunking or stripping failures of the main tires were close to this high speed/high load, spike. Undercutting appeared gradually as the tire heated up with time on the dynamometer.

LAKEHURST SET UP

The jet test tracks at NAEC, Lakehurst NJ, were used as the test bed for these tests. The test track surface is concrete. The Tire Cutting Test Vehicle is guided along the track by two I-beam rails. The debris used was either crushed limestone or bomb fragments. It was graded according to its size. Debris was placed on the ground in one of several patterns so as to impact each sidewall, rib, and groove a number of times in the test bed. The number of pieces of debris ranged from 173 to 400. An aircraft tug, an Army M-35A2 (2.5 ton) truck, and a jet cart provided the push on different tests. The tires that ran on the dynamometer were set up with to the following conditions:

RECAPPED TIRES - Thirteen tires were run under 6,486 kg (14300 lbm) load; over 12.7 mm (0.5 in), 25.4 mm (1.0 in), 38.1 mm (1.5 in), and 50.8 mm (2.0 in) debris; at 16 to 28 km/hr (10 to 17.5 mph); with no braking or turning. Each recap was a first-time recap.

NEW TIRES - Seventeen tires were run under3,311 kg (7300 lbm), 4,672 kg (10300 lbm), and 6,486 kg (14300 lbm) loads; over 25.4 mm (1.0 in), 31.8 mm (1.25 in), and 38.1 mm (1.5 inch) debris ; at 5 to 211 km/hr (3 to 131 mph); with varied turning, braking, and turning/braking combinations.

RADIAL TIRES - Four tires were run under 6,486 kg (14,300 lbm) load, over 38.1 mm (1.5 inch) debris, at 25 to 30.5 km/hr (15.5 to 19 mph), with no turning or braking.

YAW TESTS - Selected new tires had a 1° or 3° degree yaw applied. This is within the turning angle seen in normal service other than at very slow speed when pivoting about a point, as one would do when parking the aircraft.

BRAKE TESTS - Selected new tires were tested with 1.379 mPa (200 psi), 2.758 mPa (400 psi), and 3.448 mPa (500 psi) applied to the brake. To avoid locking the brake, preliminary tests were run at several brake pressure, TCTV speed, and vertical load combinations. In all tests, the TCTV was moving when the brake was engaged. On the aircraft, there is a back-pressure applied to reduce relative motion of the brake stack elements, and to overcome internal leakage so that there will always be positive response when the pilot applies the brake. The normal backpressure is 655 - 690 kPa (95-100 psi). Brake pressure during engine run up in a parking space is 5.516 - 6.895 mPa (800-1000 psi), on landing it is 9.653 - 12.411 mPa (1400- 1800 psi). The 1.379 - 3.448 mPa (200 - 500 psi) used in these tests is considered "light" braking.

TEST RESULTS

GENERAL COMMENTS - Damage from running over the debris varied greatly, as did the performance of the tires on the dynamometer. Cut maps of the extremes of damage to the tread surface may be seen in Figures 6, 7, and 8:

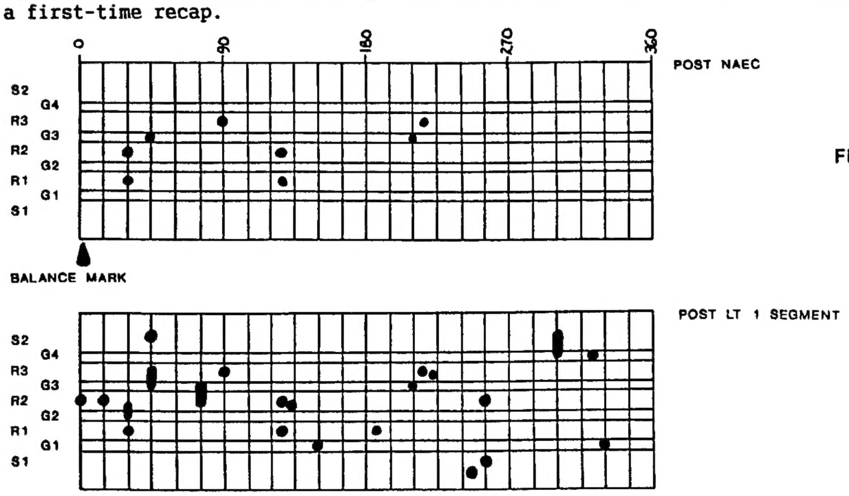


FIGURE 6: LEAST PRIMARY DAMAGE
3242-0717/X-2A RECAPPED TIRE

LEAST PRIMARY DAMAGE - Tire X-2A (recap) sustained the fewest primary cuts of all dynamometer tires run on the track at NAEC, and is presented in Figure 6. There were four primary cuts (with one

past the Cut Limit) and four primary blemishes. As it ran on the dynamometer, the primary damage increased, and secondary cuts and blemishes appeared. After lab segment LT 1, there were six primary cuts (two past the Cut Limit) and one primary blemish; and 12 secondary cuts (with two past the Cut Limit) and three secondary blemishes.

Only 1.9% of the impacts at NAEC resulted in primary cuts and another 1.9% resulted in primary blemishes. After LT 1, the number of all cuts equalled 8.7% of the number of impacts. The 450% increase in the number of cuts, and 275% increase in total damage were the top percentage increase of damage for all tires tested. The tire stripped 100% of the tread during TTO 2.

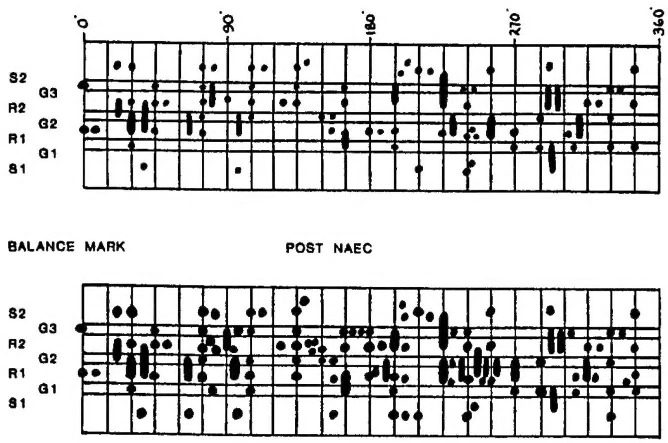


FIGURE 7: MOST PRIMARY DAMAGE
6202-0666/J-20 NEW TIRE

MOST PRIMARY DAMAGE - Tire J-20 (new) sustained the most primary cuts, and is presented in Figure 7. There were 81 primary cuts (ten past the Cut Limit) and six primary blemishes. After lab segment TTO 1, there were 86 primary cuts (11 past the Cut Limit) and no blemishes; and 27 secondary cuts (two past the Cut Limit) and three secondary blemishes.

Twenty three percent of the impacts resulted in primary cuts and 2% resulted in primary blemishes. After TTO 1, the number of all cuts equalled 33% of the impacts. This tire stripped 200 degrees of the inboard (R2) center rib during TTO 3.

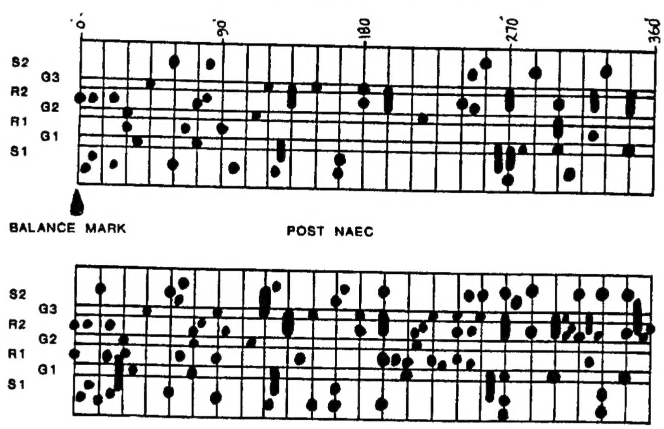


FIGURE 8: GREATEST SECONDARY DAMAGE
4044-0951/H-8 NEW TIRE

MOST SECONDARY DAMAGE - Tire H-8 (new) sustained more than the mean (40) number of cuts at NAEC, and is presented in Figure 8. There were 49 primary cuts (four past the Cut Limit) and one primary blemish. Growth of secondary damage after lab segment TTO 1 was dramatic. After TTO 1, there were 50 primary cuts (five past the Cut Limit) and no primary blemishes; and 43 secondary cuts (two past the Cut Limit) and one secondary blemish. The 43 secondary cuts after TTO 1 were the most noticed during this program.

Fourteen percent of the impacts resulted in primary cuts, and less than 1% resulted in primary blemishes. After TTO 1, the number of all cuts equalled 27% of the impacts. The tire completed 3 TTO and 3 LT segments without failure, and was removed from the test queue for the dynamometer.

The three tire groups were run in a random order on the dynamometer. The TTO and LT specifications were the same for all tires. The tires will be examined separately here.

RECAPPED TIRES

Fifteen recapped tires were run at NAEC; thirteen were tested on the dynamometer. The number of primary cuts and blemishes was generally low. An average of only 4.7% of the objects struck caused primary cuts; additional blemishes occurred.

TRACK SPEED EFFECT - All of the tires were run in a very narrow speed range: all but one were within 10% of an average test speed of 25.6 km/hr (15.9 mph). None was tested at takeoff speed.

The number of primary cuts produced is presented in Figure 9, as a function of speed in the test bed at NAEC. Individual tires had between four and 31 primary cuts, with 69% of the tires having 15 or fewer cuts. The positive slope indicates that more damage was done as the NAEC speed increased.

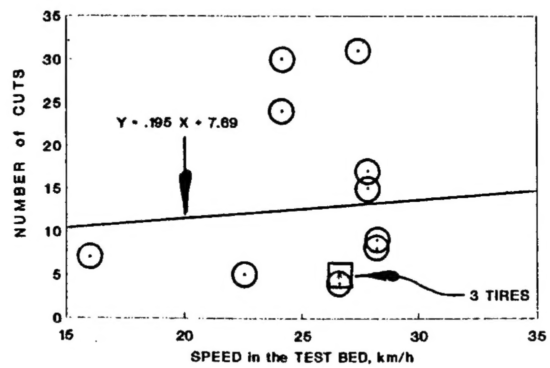


FIGURE 9: SPEED vs NUMBER OF CUTS
Recapped Tires

The mean depth of the primary cuts on each tire is presented in Figure 10. 54% of the tires were at or above the 7.1 mm (9/32 inch) Cut Limit. The negative slope results from the choice of tires. A different group might have had a different slope.

The initial mean depth of all primary cuts on all tires was 6.7 mm (8.5/32 inch). After TTO 1, the value rose to 7.2 mm (9.1/32 inch). The number and depth of primary cuts were increasing. The internal damage done becomes apparent with continued dynamometer testing.

The ratio of cuts deeper than the Cut Limit, to the total number of cuts is presented in Figure 11. Both the POST NAEC and POST TTO 1 curves have a positive slope and positive intercept. As above, the number of cuts deeper than the Cut Limit is worse with higher track speed. The POST TTO 1 curve is above the POST NAEC curve: more internal damage is revealed with additional dynamometer testing.

The number of dynamometer segments run at tire failure is presented in Figure 12. On the dynamometer, 69% of the tires failed on or before TTO 2, Test Segment 3. The negative slope indicates more damage occurred at higher track speed, which resulted in a shorter life on the dynamometer. This curve compliments the information in Figure 9.

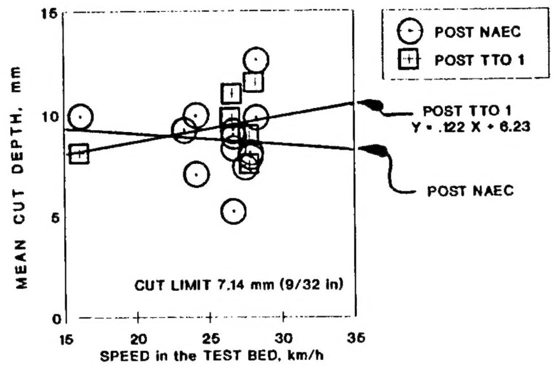


FIGURE 10: MEAN DEPTH of PRIMARY CUTS
Recapped Tires

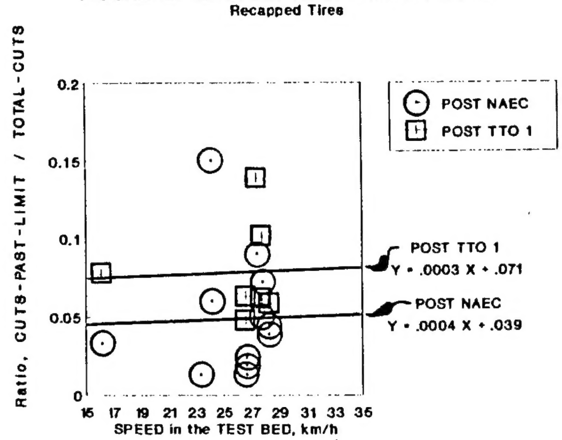


FIGURE 11: PAST LIMIT TIRE PERFORMANCE
Recapped Tires

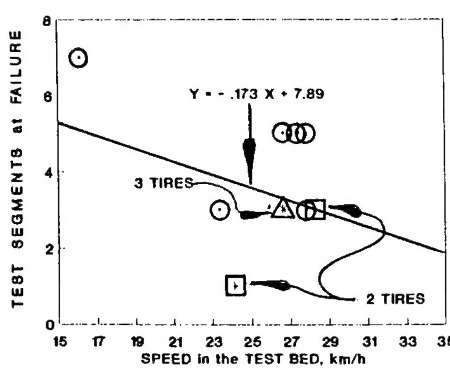


FIGURE 12: SPEED vs SEGMENTS at FAILURE
Recapped Tires

OVERALL CONDITION WITH TESTING - In general, the tires deteriorated with each run on the dynamometer. The more heavily damaged tires failed first.

Data in Figure 13 highlights the increase in the number of cuts with testing. The X-axis indicates the number of cuts before a dynamometer test segment; the Y-axis indicates the number of cuts after a dynamometer test segment. Each data point is an individual dynamometer run for an individual tire. The slope of the Post TTO 1 curve is 1.3; the intercept is 4.0. These suggest that there were an average 34% more cuts visible after the first dynamometer event than on return from NAEC.

The slope of the LT 1 curve is 1.025 with an intercept of 1.4: a 3.9% increase in the number of cuts occurred after LT 1. The increase was less than after TTO 1, but still positive, i.e. the number of cuts continued to grow. Were this trend to continue and the tire to survive, one might expect to see a cut or blemish for each impact. The tires did not, however, last long enough to produce as many cuts and/or blemishes as impacts.

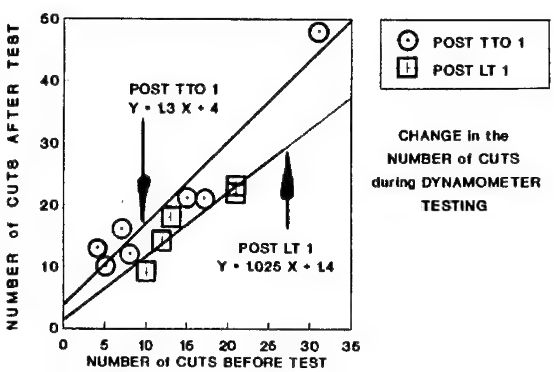


FIGURE 13: INCREASE in NUMBER of CUTS
Recapped Tires

On return from NAEC, a ratio, of the number of cuts to the number of the objects impacted, ranged from 1.3 to 15%. After TTO 1, the range narrowed to 4.8 to 13.9%; some of the tires were not remappped after TTO 1. After LT 1, the range was 4.4 to 10.6%. The numerical data from Figure 13 is presented as this ratio, in Figure 14. The curves show positive slope and intercept again. The TTO 1 curve is above the LT 1 curve.

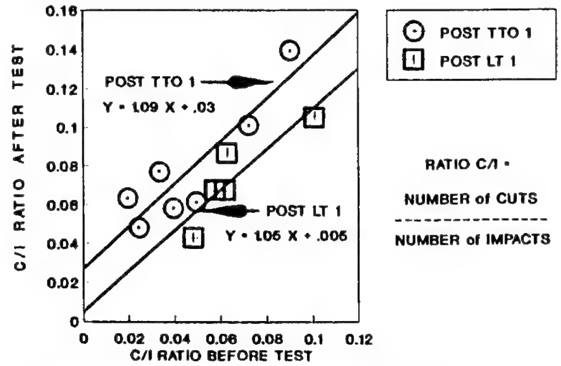


FIGURE 14: PERCENTAGE INCREASE in CUTS
Recapped Tires

The mean depth of primary and secondary cuts of all recapped tires is presented in Figure 15 and Table 4. It is interesting to note that the primary and secondary cuts have significantly different mean depths. The primary cuts are deeper. The trend in both is to deepen until the crack approaches the reinforced carcass.

The calculation is from a decreasing data pool as the tests progressed. The Post NAEC point is from 165 primary cuts on 13 tires where the Post LT 2 point is from 23 primary cuts on 2 tires.

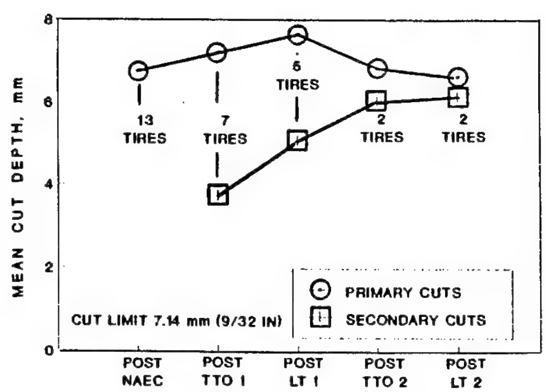


FIGURE 15: MEAN CUT DEPTH
Recapped Tires

Table 4: Overall Damage Progression of Recapped Tires

Segment:	Post NAEC	Post TTO 1	Post LT 1	Post TTO 2	Post LT 2
Number of Tires	13	7	5	2	2
Primary Cuts					
Total number of cuts	165	89	55	22	23
Mean depth (1/32 in)	8.5	9.06	9.63	8.16	8.0
Secondary Cuts					
Total number of cuts		52	31	14	14
Mean depth (1/32 in)		4.7	6.37	7.59	7.71

INDIVIDUAL CONDITION WITH TESTING - Changes in the mean cut depth of primary cuts of seven tires are presented in Figure 16. Damage is unpredictable. An increase or decrease in mean depth on one segment might be followed by the opposite after the next segment. The changes include the cut becoming shallower, deeper, or closing; new cuts appearing; or cuts going unchanged.

The deepest primary and secondary cuts at the beginning of the last dynamometer test segment are presented in Figure 17. The primary cuts average 15.9 mm (20/32 inch) deep, more than twice the 7.1 mm (9/32 inch) Cut Limit. The secondary cuts average 7.9 mm (10/32 inch) deep which is just over the Cut Limit. As was noted above, 69% of the tires failed on or before TTO 2, Test Segment 3.

The average life of these 13 recapped tires on the dynamometer was 3.5 test segments. Operational field experience with the recapped tires was poor: fewer landings per tire change and more catastrophic failures than the new tire. A comparison test was completed using five undamaged recapped tires. They were run on TTO schedules only. As noted in Figure 17, undamaged tires failed on segments 2, 3, 13, 14, and 19.

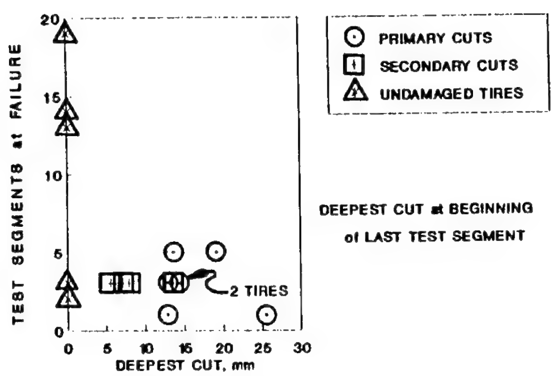


FIGURE 17: DEEPEST CUT at FAILURE
Recapped Tires

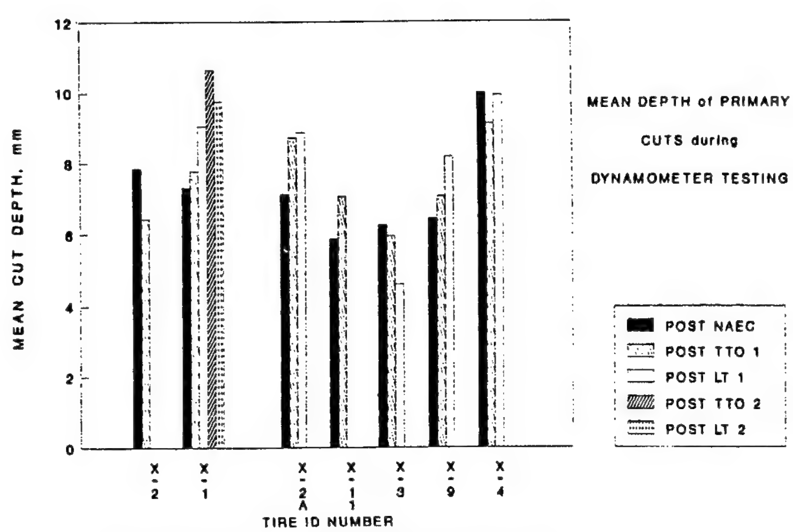


FIGURE 16: DEPTH CHANGES during TEST
Recapped Tires

FAILURE MODES - Twelve of thirteen recaps experienced "general" tread failures on the dynamometer. These included stripping 15 - 100% of a single rib, stripping the entire tread, chunking around the perimeter, and/or undercutting at least one rib. Undercutting, which may not be directly related to debris impact, occurred on three tires.

NEW TIRES

Eighty six new tires were run at NAEC. Sixteen were run on the dynamometer.

TRACK SPEED EFFECTS - The track speed for all tires ranged between one and 270 km/hr (one to 168 mph); those that were dynamometer tested ran between five and 211 km/hr (three to 131 mph). This top speed is one half takeoff speed.

The number of primary cuts produced is presented in Figure 18. Dynamometer tires had between seven and 81 primary cuts, with 59% having 40 or fewer cuts. The trend noted with recaps is repeated: more cuts at higher track speeds.

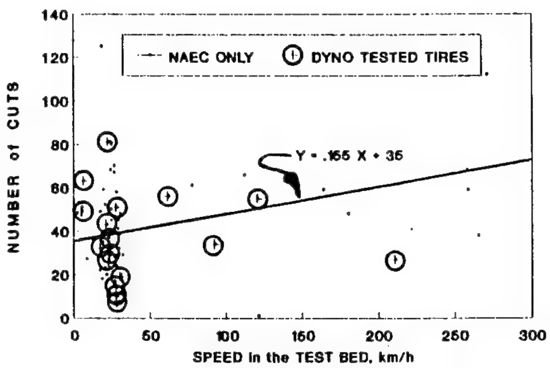


FIGURE 18: SPEED vs NUMBER of CUTS
New Tires

The mean depth of the cuts on each tire is presented in Figure 19. 35% of the tires were at or above the 5.6 mm (7/32 inch) Cut Limit. This compares to 54% of the recaps that were at or above a deeper Cut Limit. The initial mean depth of all cuts on all dynamometer tires was 4.9 mm (6.17/32 inch). This compares to 6.7 mm (8.5/32 inch) for the recaps. A Shore Type A durometer comparison of the new and recap tire materials may explain this difference. The recaps registered 10% lower value (softer compound). As was noted above, the service life of recaps was not as good as the new tires. Recaps F-16 main tires were removed from flight status.

The ratio of cuts deeper than the Cut Limit, to the total number of cuts is presented in Figure 20. All three curves have a positive slope. The amount of damage is higher for the new tires than with the recapped tires, but the performance trend is reversed: POST TTO 1 data is below POST NAEC data. In a number of tires, the number of cuts dropped between NAEC measurements and POST TTO 1 measurements.

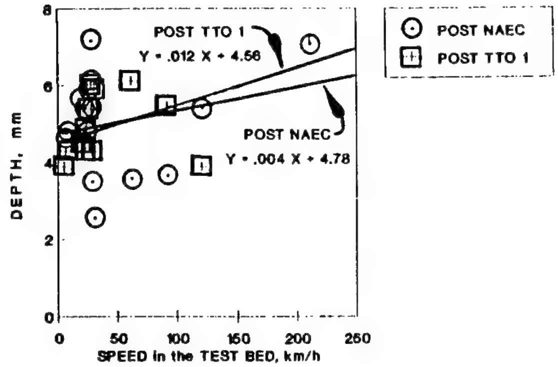


FIGURE 19: MEAN DEPTH of PRIMARY CUTS
New Tires

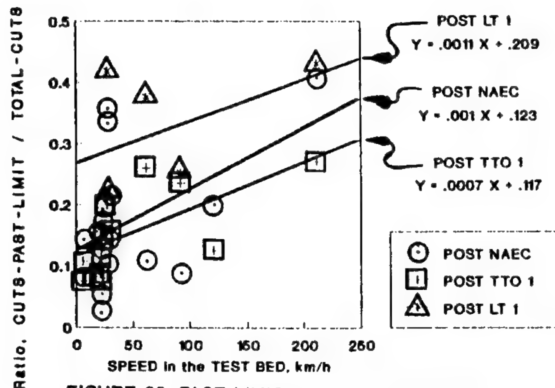


FIGURE 20: PAST LIMIT TIRE PERFORMANCE
New Tires

The number of test segments run at tire failure is presented in Figure 21. On the dynamometer, 64% of the tires failed on or before LT 3, Test Segment 6. The negative slope of the curve compliments the information in Figure 12: more damage occurred at higher track speed, resulted in shorter life on the dynamometer. This is similar to the trend seen on the recaps.

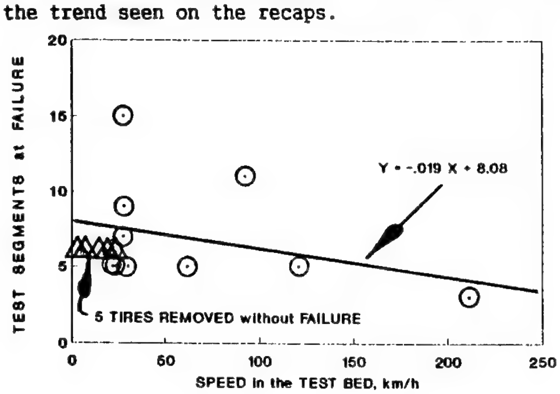


FIGURE 21: SPEED vs SEGMENTS at FAILURE
New Tires

OVERALL CONDITION WITH TESTING - Like the recaps, the new tires deteriorated with each run on the dynamometer. The number of cuts before and after each test segment in Figure 22 is similar to recapped tire data in Figure 13, except that the slope and intercept are different. New tire POST TTO 1 data indicates a 30% increase in the number of cuts over POST NAEC levels; it was 34% for the recapped tires. New tire POST LT 1 data indicates an 8% decrease in the number of cuts over POST TTO 1 levels; it was a 3.9% increase for the recapped tires. A difference in tread material, noted with the Shore durometer test, may explain this change. On landing, the high heat created by spin up seems to temporarily glue some cuts back together.

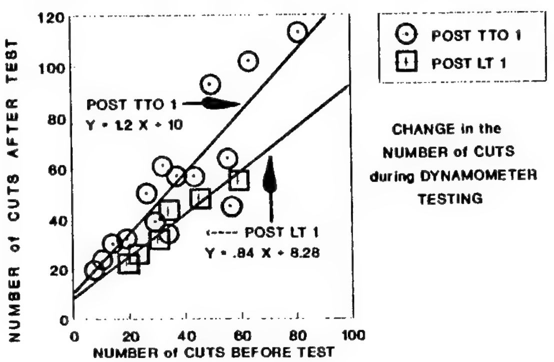


FIGURE 22: INCREASE in NUMBER of CUTS
New Tires

In Figure 23, the data from Figure 22 is presented as the ratio of cuts-per-impact before and after each dynamometer test. The slope and intercept of new tire POST TTO 1 curve is greater than it was for recapped tires curve. The new tire POST LT 1 curve has an 18% decrease over POST NAEC data; the recapped tire POST LT 1 curve had a 5.5% increase.

The mean cut depth of primary and secondary cuts of all tires is presented in Figure 24 and Table 5. The new tire trend is more severe than it was for the recapped tires: the mean cut depth increased above the Cut Limit with dynamometer tests. The data pool shrank as the test continued because of tire failures or removals after three TTO and LT segments had been completed.

The greater damage may also reflect the conditions of test at NAEC: twice as many new tires ran over 38 mm (1.5 inch) rocks than did recapped tires; and some of the new tires ran at "high" speed (above 48 km/hr - 30 mph), while no recap ran over 29 km/hr (18 mph).

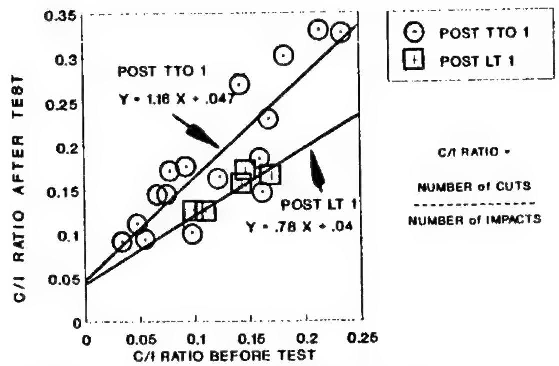


FIGURE 23: PERCENTAGE INCREASE in CUTS
New Tires

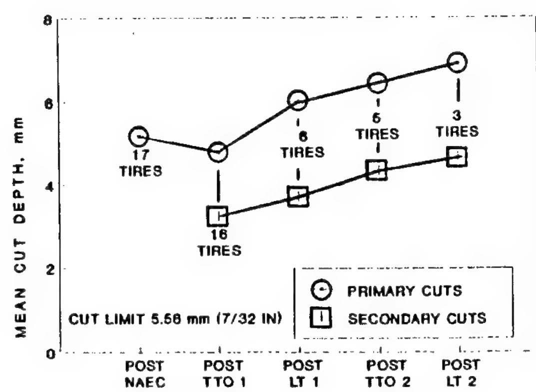


FIGURE 24: MEAN CUT DEPTH
New Tires

Table 5: Overall Damage Progression of New Tires

Segment:	Post NAEC	Post TTO 1	Post LT 1	Post TTO 2	Post LT 2
Number of Tires	17	16	6	5	3
Primary Cuts					
Total number of cuts	633	611	146	138	88
Mean depth (1/32 in)	6.53	6.02	7.55	8.11	8.67
Secondary Cuts					
Total number of cuts		272	91	95	59
Mean depth (1/32 in)		4.08	4.67	5.45	5.86

INDIVIDUAL CONDITION WITH TESTING - Changes in the mean cut depth of primary cuts of seventeen new tires are presented in Figure 25. No rational pattern can be drawn from this data. The same was true of the recapped tires.

The average life of new tires on the dynamometer was 6.9 test segments.

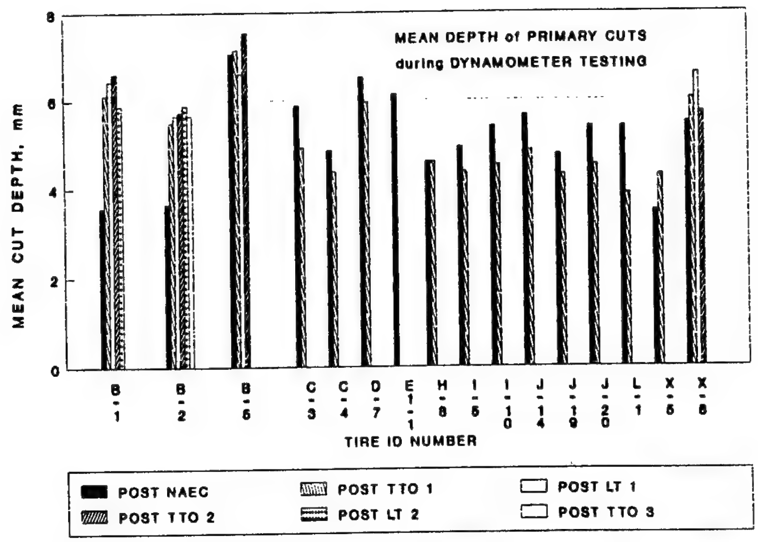


FIGURE 25: DEPTH CHANGES during TEST
New Tires

FAILURE MODES - Five of the new tires were removed from the test queue after six test segments without failure. The other twelve were removed when either 56 - 100% of a single rib stripped, the entire tread stripped, the tread chunked around the perimeter of the tire, and/or at least one rib was undercut. Undercutting was noted on one tire.

RADIAL TIRES

Four new prototype radial tires were run at NAEC; all four were run on the dynamometer. Tire H-4 was a different design than H-1, 2, and 3, and produced different results than the other tires.

SPEED EFFECTS - The track speed ranged from 24.1 - 31.4 km/hr (15 - 19.5 mph), over 38.1 mm (1.5 inch) limestone, under a 6,583 kg (14,500 lbm) load.

The number of primary cuts produced is presented in Figure 26, as a function of speed in the test bed at NAEC. The "newer" design H-1, 2, and 3 produced 2/3's fewer cuts than the "earlier" design H-4. Of the 110 primary cuts on all four tires POST NAEC, one half of the cuts were on H-4. Because of the small number of tires, run in a small speed range, there is not enough data to draw a useful conclusion.

The mean depth of cuts on each tire is presented in Figure 27. Unlike the production bias tires that were tested, these prototype radial tires did not have a Cut Limit label cast on the sidewall. The POST TTO 1 data shows the familiar positive slope and intercept with speed. If H-4 is removed from the data, the initial mean depth of all cuts in the other tires is 4.0 mm (5.036/32 inch).

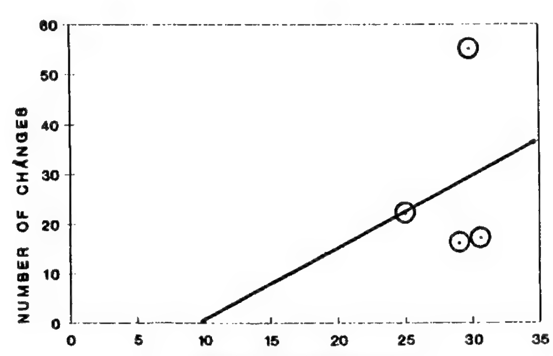


FIGURE 26: SPEED vs NUMBER of CUTS
Radial Tires

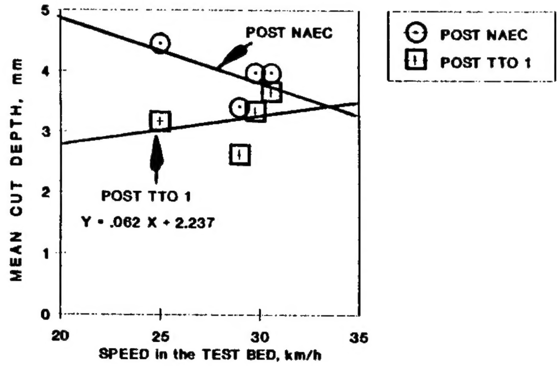


FIGURE 27: MEAN DEPTH of PRIMARY CUTS
Radial Tires

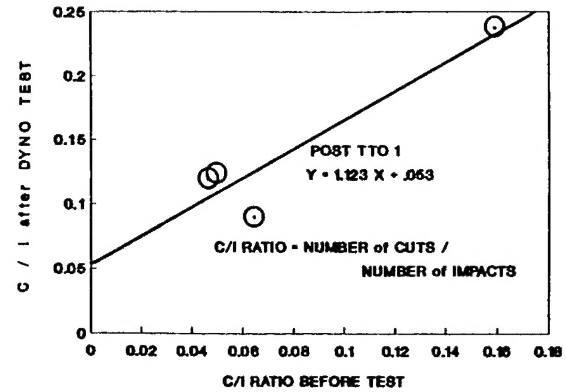


FIGURE 29: PERCENTAGE INCREASE in CUTS
Radial Tires

OVERALL CONDITION WITH TESTING - Data in Figure 28 suggests a 33% increase in number of cuts after TTO 1. This performance is similar to the new and recapped tires. POST LT 1 data is not available, as the radial tires were only remapped after TTO 1.

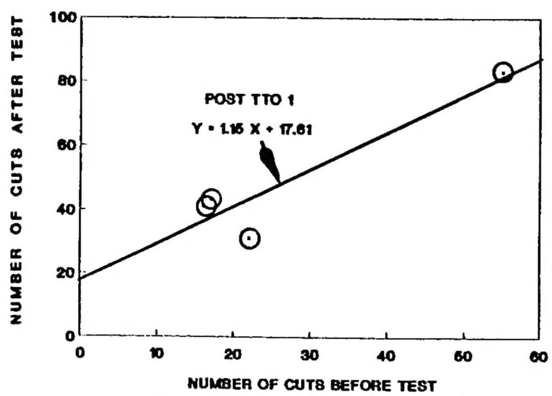


FIGURE 28: INCREASE in NUMBER of CUTS
Radial Tires

In Figure 29, the data from Figure 28 is presented in a ratio of cuts per impact form. An increase of 18% is suggested. This is higher than the recaps, but lower than the new tires.

The mean depth of primary and secondary cuts of all tires is presented in Figure 30. The data population is very small, and no useful conclusions may be drawn.

INDIVIDUAL CONDITION WITH TESTING - Changes in the mean depth of primary cuts of the four tires are presented in Figure 31, as each tire was tested on the dynamometer. All four experienced a reduction of depth with testing. No further maps were made after TTO 1, so no other data is available.

FAILURE MODES - The damage to tires H-1 and 3 was very similar, in the number of cuts, C/I ratio, and mean depth of primary cuts. H-3 failed on TTO 3, Test Segment 5. H-2 suffered 30 -40% more cuts and C/I, and had a mean depth 12 - 30% greater than H-1 and H-3. H-4 experienced 50% of all cuts measured, C/I ratio was three times higher than the other tires, but had a mean depth of primary cuts similar to the other cuts.

Tires H-1 and H-2 were removed after three TTO and three LT segments had been completed without failure.

H-3 stripped the entire tread. It showed evidence of poor adhesion of the tread to the reinforcing cord. When it failed, the tread came off, followed by the reinforcing cord. It unwound like the outer layer on a ball of string. The cord showed virtually no adhesion to the rubber. It could be pulled away from the carcass very easily by hand.

H-4 sustained more damage at NAEC and failed sooner than the other radial ply tires. A broken reinforcement or carcass cord stuck through the tread when received from NAEC. This damage seemed to precipitate the stripping failure of the tread.

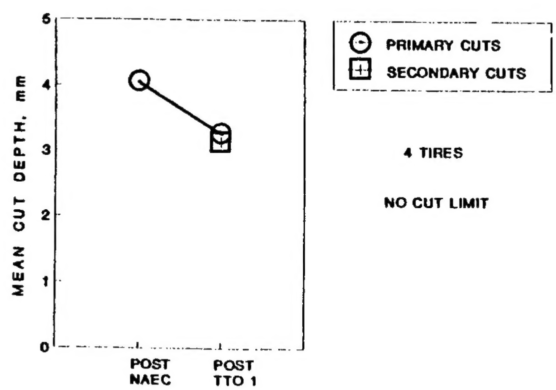


FIGURE 30: MEAN CUT DEPTH
Radial Tires

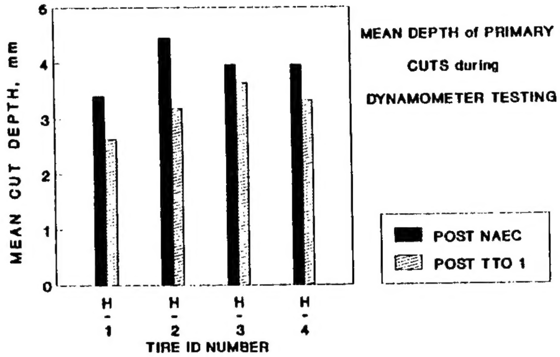
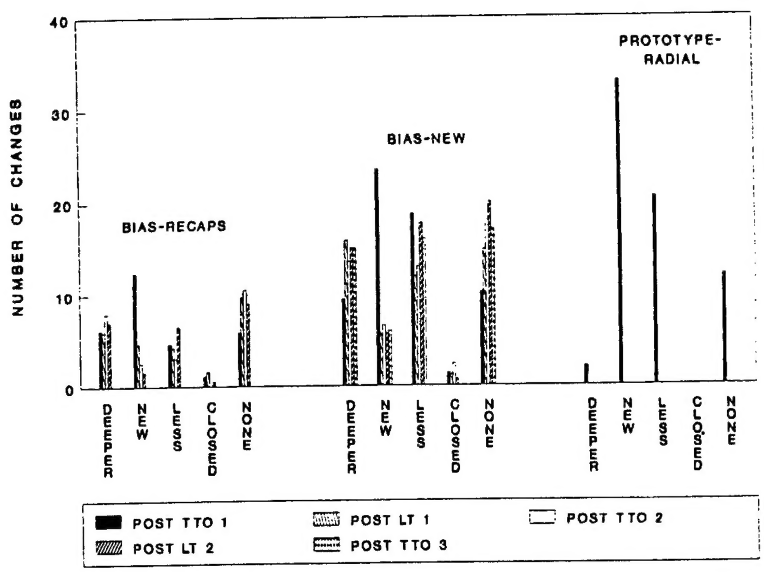


FIGURE 31: DEPTH CHANGES during TEST
Radial Tires

FIGURE 32: CUT ACTIVITY during TESTING



OTHER FACTORS

Tread stripping was common to thirteen of the thirty six tires that went on the dynamometer. There were other flaws noted during the tests, including the following:

(1) Two of the new tires (D7 and L1) showed evidence of heat related damage (reversion of the rubber) near a cut location. This heat failure may have precipitated the tread failure.

(2) Several of the tires, including one radial tire, had a broken reinforcement/carcass ply sticking through the tread before the general tread failure.

FINAL PATTERN

As one may see in Figure 32, the three tire designs had different amounts of activity:

Cuts grew DEEPER
NEW cuts opened
Cuts became LESS deep
Cuts CLOSED to become a blemish or disappear entirely
or NONE of the above, indicating no change in the cut depth, or a blemish that stayed a blemish

In all three groups, the number of NEW cuts was greatest after TTO 1. The DEEPER, LESS, and NONE were similar test to test, within like tires, i.e. performance of all recaps was similar. The activity of the recaps was the lowest, but their durability was also the lowest. The changes of the

prototype radial tires was the greatest, but they were not mature tires.

CUT DEPTH ACTIVITY - NEW cuts are indications of secondary damage. The number of new cuts is very high after the first taxi-takeoff segment. The activity then trails off greatly. The number of cuts that closed is very small throughout the tests. As was noted with the bias ply tires, the depth of the cuts increases with more test segments on the dynamometer.

CONCLUDING REMARKS AND OBSERVATIONS

Several trends may be noted in these tests:

1) With increased impact speed, the damage to the tire increases:

more cuts, that grow proportionally deeper
more greater-than-the-Cut-Limit cuts
shorter life expectancy on the dynamometer

2) The size of the debris had an effect on the cuts: larger debris produced more cuts deeper than the Cut Limit.

3) Twice as many new tires ran over 38.1 mm (1.5 inch) debris as did recapped tires; the rate of cuts deeper than the Cut Limit was twice as high for the new tires than for the recapped tires. The number of cuts stayed proportionally higher throughout the dynamometer tests.

4) The tread material and manufacturing techniques produced noticeable differences in dynamometer performance:

The recap material failed in 3.5 test segments, where the original new tread material failed in 6.9 test segments. The new tire might have had a better average if the five tires that were removed after three TTO and LT segments (without failure) had been run to destruction.

"A" scale Durometer readings of the recapped tires were lower than the new tires.

5) The number of cuts increased after each test segment in the recaps. In the new tires, it increased after TTO 1 (at a lower rate than the recaps), but decreased after LT 1. Toughness and tear resistance of the material may be involved. Twice as many deeper than the Cut Limit in the new tire didn't effect the durability; again, they lasted twice as long as the recaps.

6) Many more of the tire failures were observed near the end of the TTO segment, than during the LT. Incipient tire failure can not be predicted in the field. The load added to the main tire when the nose is lifted off can be reduced by eliminating an external store on the aircraft. A combat sortie may be changed, but if the plane is damaged by flying debris or crashes because of a cut-related tire failure, it won't be productive then, either.

7) Cut or blemish damaged tires are dangerous in that they are unpredictable. Secondary damage to the aircraft may be caused by pieces of the damaged tire striking the aircraft.

8) Major tread loss may be due to poor adhesion between the carcass and tread, or between the reinforcing plies and the tread. While it may have been triggered by cut damage, this adhesion failure may also be a manufacturing flaw: a number of chunking failures began where no cuts were observed.

9) Chemical reversion may occur locally and cause a cut to close for a flight segment. The integrity of the tread can not be guaranteed; however, once damage that excedes the Cut Limit has been noticed, safety should be pursued by changing the tire at the earliest opportunity. Tread stripping and undercutting may result from cut damage; or from poor adhesion, or from chemical breakdown caused by high heat. Half of the tires tested failed because of tread stripping and/or undercutting. In many of the stripping cases, the failure was no where near a cut. The carcass often showed evidence of poor adhesion between the tread and the carcass.

RECOMMENDATIONS

Goodyear F-16 main tires have 121° C (250° F) Spot Surface Temperature Limit (SSTL). From past experience, surface temperatures of Type VII tires may run near these levels under normal operations. Relative motion of the sides of a cut may elevate the local operating temperature to or above these SSTL's. The flaw may change shape quickly when surface temperatures approach these high levels. Future work in this area should include the use of an infrared strip camera and a visual image camera, so that local temperatures can be examined on the whole surface of the tire, at damage sites and where there is no damage.

Thermal damage destroyed several tires at locations where no cuts were present. Further, cuts closed for a few dynamometer segments, only to reopen. Higher temperature materials should be pursued for a front line tire that must survive on a hostile post-attack airfield.

At the factory, quality control inspections must be improved in number and in quality. The tires that failed because of stripping may have had similar life spans even if they had not been cut, i.e. the undamaged recaps that only lasted two or three dynamometer segments.

The relatively low ratio of cuts per impact, C/I, suggest a follow-on program of cut progression. Individual cuts should be created with a knife, in specific patterns, rather than by running over debris. This program provided data on cut locations and dimensions, and provided a supply of cut tires for the dynamometer. The hand cut tires should be examined after each dynamometer event to see if the pattern observed here (unpredictable cut growth/closure) continues. The effect of debris related internal damage can not be estimated by eye. The test tire should be examined for internal delamination/ply failure before and after it is damaged, and occasionally during dynamometer tests by dismounting, and examination with a shearo-

graphy test machine.

NOMENCLATURE

G	groove
LGDV	Landing Gear Development Center, Flight Dynamics Directorate, Wright-Patterson AFB
OH	
LT	Landing-Taxi segment. See Figure 3
NAEC	Naval Air Engineering Center, Lakehurst NJ
R	rib
SW	sidewall
TCTV	Tire Cutting Test Vehicle
TTO	Taxi-Takeoff segment. See Figure 2

Primary Cuts	cuts that were present on return from NAEC
Secondary Cuts	cuts that were observed after dynamometer segments

POST NAEC	measurements made after the tire was run on the track at NAEC
POST TTO 1	measurements made after the tire had completed Taxi-Takeoff segment number 1 on the dynamometer
POST LT 1	measurement made after the tire had completed Landing-Taxi segment number 1 on the dynamometer

UNITS

°C	temperature, degrees centigrade
C/I	ratio, cuts per impact
cm sq	square centimeters
°F	temperature, degrees fahrenheit
kg	mass, kilograms
km/h	speed, kilometers per hour
kPa	pressure, kilo-pascals
lbm	mass, pounds
m	meter
mm	millimeter
mPa	pressure, mega-pascals
mph	speed, miles per hour
psi	pressure, pounds per square inch

ACKNOWLEDGEMENTS

This program was under the direction of Kenneth P. Schwartz, at Wright-Patterson Air Force Base.

The author wishes to thank Gwendolyn A. Patterson, William K. Smith, Paul Ulrich, and Paul Wagner, Flight Dynamics Directorate; Lt. Colonel Donna C. Herge, Air Force Institute of Technology; and Dr. Gerald E. Meike, Wright State University, for their technical support.

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APPENDIX: DAMAGE DESCRIPTIONS

CUT - a break in the surface of the tread. The length is greater than 1.6 mm (1/16 inch); the depth is greater than 0.8 mm (1/32 inch).

PUNCTURE - a cut with length less than 1.6 mm (1/16 inch), depth greater than 0.8 mm (1/32 inch).

UNDERCUT - a flaw that extends under the tread, parallel to the surface. Chemical reversion of the rubber compounds often occurs in an undercut area. The undercut is created by side load on the tread, and/or by heat. Any amount of undercutting is cause for immediate removal.

HEAT BLOW - a vent of gases from within the tread material. A small surface hole may connect to an interior pocket within the tread, or to a delamination of plies within the carcass of the tire.

BLEMISH - a non-invasive deformation of the tire surface. It may be an external indication of internal damage. Many blemishes opened up into cuts during dynamometer testing.

SCUFF - a general surface abrasion that occurred on tires that had a yaw angle other that zero degrees.

PRIMARY/SECONDARY DAMAGE - all cuts and blemishes, as described above, that were recorded after the run at NAEC, are referred to as "Primary Damage." This damage was tracked through the rest of the tire's life on the dynamometer. "Secondary Damage" is any flaw that was noticed after dynamometer testing. The damage from individual test segments was recorded.